Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **464,** 2499–2501 (2017) doi:10.1093/mnras/stw2474
Advance Access publication 2016 September 28

Erratum and Addendum: Smoothed particle magnetohydrodynamic simulations of protostellar outflows with misaligned magnetic field and rotation axes

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Key words: accretion, accretion discs – MHD – stars: formation – stars: jets – stars: winds, outflows.

The paper 'Smoothed particle magnetohydrodynamic simulations of protostellar outflows with misaligned magnetic field and rotation axes' was published in MNRAS 451, 288 (2015) (hereafter 'the Original Paper').

The calculations presented in that work were performed using a smoothed particle magnetohydrodynamics (SPMHD) code known as SPHNG. Unfortunately, a bug was present in the integrator that was used to evolve the magnetic field. The bug caused an 'instability' in some SPMHD calculations, whereby poor energy conservation could produce an explosion. In the Original Paper, the cause of the poor energy conservation was incorrectly ascribed to a deficiency in our SPMHD scheme (discussed in section 2.2 of the Original Paper), and we are grateful to Dobbs (private communication) for discovery of the underlying cause.

In the Original Paper, we proposed a modified SPMHD method – the average h method – that employed an average smoothing length term in some of the MHD equations to correct the spurious 'instability' (see Section 2.2). In this addendum, we compare results from calculations using that method with the integrator bug (i.e. calculations as published in the Original Paper) with otherwise identical calculations that use the standard SPMHD equations (without the average h method) and a correct integrator. We show that the results of the calculations using each method exhibit some differences, particularly on small scales. These differences do not affect the conclusions in the Original Paper on the evolution of outflows and jets, and how they depend on the alignment between the field and the rotation axis. However, they do eliminate some of the fine structures that were seen at scales of $\lesssim$100 au.

We note that as a result of the correction of the integrator bug, the 'average h' formalism is redundant and we no longer recommend it be used. Nonetheless, our observations in Lewis et al. (2015a) that the choice of averages used for smoothed particle hydrodynamics (SPH) equations are fairly flexible are still correct and this may still be of some interest for SPH schemes, which use an averaged smoothing length as opposed to a Price & Monaghan (2004) scheme.

Section 1 of this addendum discusses the integrator bug in detail and then in Section 2, we provide a side-by-side comparison of calculations from the Original Paper with those using a corrected integrator and without the average h equations.

1 THE INTEGRATOR BUG

We use a two-stage second-order Runge–Kutta–Fehlberg integrator (RK1(2) in Fehlberg 1969) to evolve all fluid parameters (e.g. v^i), except the density,[1] in time. This integrator can be represented for an arbitrary quantity, φ as

$$\varphi_{t+1/2} = \varphi_t + \frac{\Delta t}{2}\dot{\varphi}_t \tag{1}$$

for the first half of the time-step, Δt, and

$$\varphi_{t+1} = \varphi_t + \frac{1}{256}\dot{\varphi}_t\Delta t + \frac{255}{256}\dot{\varphi}_{t+1/2}\Delta t \tag{2}$$

for the complete time-step. In Lewis et al. (2015b) and all earlier papers using SPHNG, this was implemented correctly for all fluid quantities except for the magnetic field vector, B^i. There, instead of the second term on the right-hand side of equation (2) being

$$\frac{1}{256}\left.\frac{\mathrm{d}B^i}{\mathrm{d}t}\right|_t \Delta t, \tag{3}$$

the value from when $t = 0$ was erroneously retained, in effect replacing this term by

$$\frac{1}{256}\left.\frac{\mathrm{d}B^i}{\mathrm{d}t}\right|_0 \Delta t. \tag{4}$$

Superficially, this appears to be *very* serious, however, a crucial property of our setup makes it less so: at $t = 0$, the rate of change of the magnetic field is very small.

Therefore, this error is somewhat equivalent to adding a small constant stress into the field, and even then this only contributes at the level of $1/256 \approx 0.5$ per cent to the magnetic field evolution. Nonetheless, this does cause errors, particularly on smaller length-scales, because these correlate with Δt being very small due to individual timestepping: values of $\Delta t/(\Delta t)_0 < 1/2^8$ are common in the central area of the calculation. These regions are also where more complicated fields are present, and particularly field geometries that are very different to those seen at $t = 0$.

This mistake in the integrator placed restrictions on previous calculations. For example, when using sink particles with accretion radii smaller than $\approx$5 au, 'explosions' occurred due to non-conservation of energy. At the time, these were erroneously ascribed to uncontrolled growth in the magnetic divergence or to errors calculating certain MHD quantities in very steep density gradients. Instead, the reason for the apparent stability of the larger accretion

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[1] This is set self-consistently with the smoothing length such that $h \propto 1/\rho^{1/\nu}$.

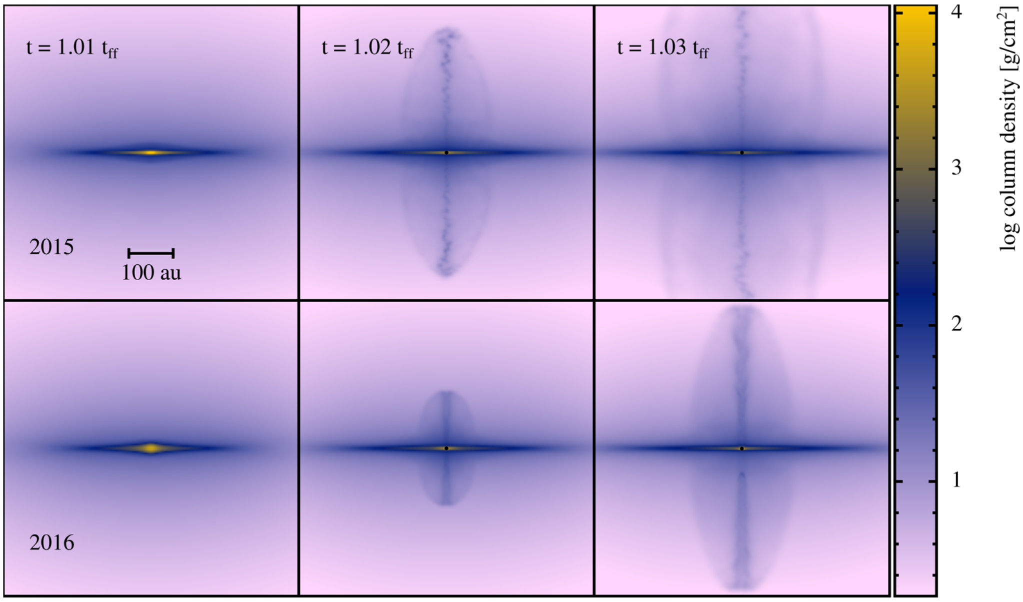

Figure 1. Comparison between results obtained using the incorrect integrator and SPMHD formalism of Lewis, Bate & Price (2015b) (2015), with those obtained using a correct integrator and the standard SPMHD formalism (2016). The initial conditions had the magnetic field aligned with the rotation axis ($\vartheta = 0^\circ$), and the mass-to-flux ratio was $\mu = 5$. In addition to the integrator bug, the 2015 code excessively smooths the magnetic field that reduces the growth rate of the field leading to a reduction in the magnetic pressure support in the collapsing cloud. This causes a slightly quicker collapse of the cloud core and thus, the slightly earlier launching of an outflow. The 'kinks' or 'wobbles' within the jet are artefacts of the integrator bug, not the modified SPMHD formalism. However, the jets produced have similar velocities with $|v_z| \approx 8\,\mathrm{km\,s^{-1}}$.

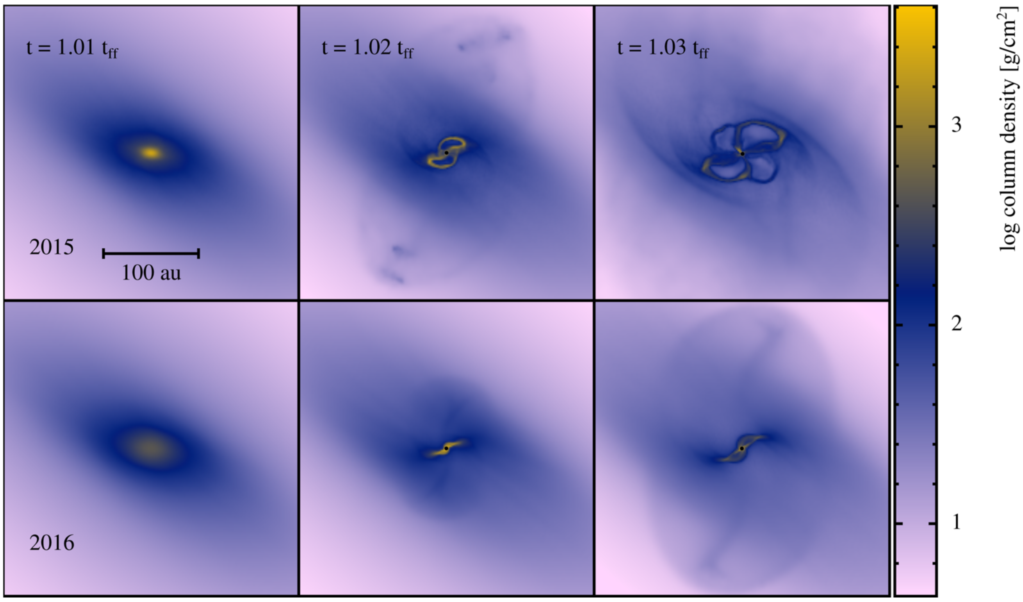

Figure 2. Comparison, similar to Fig. 1, but for $\vartheta = 45^\circ$. For this geometry, significant differences in the small-scale structure are observed, but the larger structures are comparable (although less evolved at a given time for the 2016 calculation). In particular, the 2016 calculation no longer produces the loop structures seen for the 2015 calculation.

radii calculations is that these simply did not include a region where both Δt was sufficiently small *and* the field geometry sufficiently complex to become 'unstable'.

2 COMPARISON OF CALCULATIONS

To assess the impact that the integrator bug had on previous work, here we compare the results from calculations that were performed using the method from the Original Paper (i.e. the average h formalism and the integrator bug), and with the standard SPMHD formalism the correct integrator. We will refer to the former as the '2015' calculations, and the latter as the '2016' calculations. We perform calculations with two different types of initial conditions that are representative of the calculations found in the Original Paper: one in which the magnetic field is initially aligned with the rotation axis, and one where it is inclined at $\vartheta = 45^\circ$ to the rotation axis. Both calculations have an initial mass-to-flux ratio of $\mu = 5$.

The use of the average h formalism results in a slightly suppressed magnetic field and hence a slightly quicker collapse in the 2015 calculations, as seen in the projection in Fig. 1. A comparable disc structure has formed in both calculations, but the 2015 calculation is clearly slightly more evolved at $t = 1.01\,t_{\rm ff}$, which similarly results in a jet that has travelled further at $t = 1.02\,t_{\rm ff}$. The two jets are very similar, and the two calculations have similar maximum jet velocities of $8\,{\rm km\,s^{-1}}$. However, the 2016 calculation no longer exhibits the 'kinks' or 'wobbles' seen in the 2015 calculation (see also Price, Tricco & Bate 2012). These were an artefact of the integrator bug. We show the results from the $\vartheta = 45^{\circ}$ calculations in Fig. 2. Clearly, the small-scale structures – the magnetic loops – are no longer present. However, both models have produced jets that are misaligned from the rotation axis.

The average h method 'saved' the calculations from the Original Paper by smoothing the magnetic field, which reduces the growth rate of the field and hence the field strength near the sink particle. The consequently weaker field was then more robust against the extra stress term introduced by the integrator. However, the integrator error, not the average h method, is responsible for the spurious small-scale structures.

We therefore conclude that, notwithstanding the presence of both the integrator bug described in Section 1 and the use of the modified SPMHD method described in section 2.2 of the Original Paper, the results from that paper remain valid on larger length-scales, but they produce unphysical structures on small scales. The conclusions in the Original Paper on how the jet properties depend on the alignment between the field and the rotation axis are correct (e.g. that no substantial outflow is obtained when $\vartheta > 60^{\circ}$). The small-scale features (kinks inside the jets, and magnetic loops around the protostars and psuedo-disc), however, were numerical artefacts.

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